Temporal integration: reflections in the M100 of the auditory evoked field

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Previous work investigating temporal integration in the formation of the auditory evoked field component, M100, indicates an accumulation of stimulus attribute information in the processes underlying the M100 response with a temporal window for this integration of ~25–32 ms. We investigate the influence of stimulus duration on M100 amplitude using sinusoidal tone stimuli of increasing duration under two experimental conditions: constant intensity, and constant energy (with stimulus intensity decreasing as duration increased). We report that M100 amplitude increases with stimulus duration up to a point of saturation at ~40 ms; importantly, this dependence holds in both experimental conditions, despite differing stimulus intensities. Thus we conclude that (within this ~40 ms temporal window) stimulus duration itself, and not integrated energy, determines M100 amplitude. *NeuroReport* 11:2723–2726 © 2000 Lippincott Williams & Wilkins.

Key words: Auditory cortex; Evoked response; Magnetoencephalography; M100; Stimulus duration; Sound onset; Temporal encoding; Temporal integration; Timing

INTRODUCTION

The onset of a sound in the auditory scene contains important alerting cues for the auditory system, providing information regarding the location of the sound source as well as the nature of the sound itself. The relative importance of the onset of an auditory signal is reflected in neural response properties of the ascending auditory system: the majority of neurons throughout the system respond to the onset of a sound [1]. There is evidence that onset characteristics (such as intensity, rise time) of the earliest portion of the auditory signal are processed by the auditory system using a relatively fine-grained analysis, an analysis that differs for the remainder of the signal [1,2]. This perceptual bias for information contained early in an auditory signal is thought to aid the auditory system in segregating information in the auditory scene into meaningful events.

Neural correlates of the perceptual bias for sound onsets have been provided in studies using electromagnetic-based methods such as EEG and MEG to record auditory evoked responses that are time-locked to stimulus onset. Studies using MEG to record cortical response to auditory stimuli have provided evidence in support of the differential processing of the initial portion of sounds. The M100 component, occurring roughly 100 ms after stimulus onset, is modulated in amplitude and latency as a function of stimulus properties (such as stimulus intensity or duration) that occur at the onset. For example, the amplitude of the M100 component increases as stimulus duration lengthens, indicating that there is an accumulation of stimulus attribute information over time [3,4]. This effect typically reaches saturation with stimulus duration of ~20–30 ms, with response amplitudes plateauing for stimuli of longer durations. These findings are in good accord with earlier work using electrophysiological techniques to record auditory evoked potentials in response to tones that differed both in duration and in intensity [5]. These researchers reported increased evoked potential amplitude as stimulus duration increased from 0 to 30 ms and as stimulus intensity increased from 25 to 85 dB SPL. These effects reached plateau at durations >30 ms and were similar across the four intensity levels tested. The neuromagnetic M100 component amplitude also shows stimulus intensity dependence, with M100 amplitude increasing with increasing intensity of a sound signal [6–9]. Thus, the amplitude of the 100 ms component of the auditory evoked responses demonstrates both a temporal and an intensity dependence, with increased response amplitudes as a function of both longer stimulus durations and higher intensity levels.

Additional evidence pointing to the critical importance of a finite (and short) temporal window in determining subsequent features of the measured evoked response is provided by studies using MEG to investigate temporal integration properties pertinent to the M100 component. Auditory evoked responses to click trains presented at various presentation rates were recorded and the duration of the temporal window of integration for the auditory M100 was approximated at ~25–32 ms based on the interclick interval required to modulate M100 latency and amplitude [10,11].

In the present experiment, we investigate the relative contributions of stimulus attributes, intensity and duration, in the accumulation processes and in particular the temporal window of integration pertinent to the formation of the M100 peak. In order to characterize the relative contributions of stimulus intensity and duration on the accumulation processes underlying the M100 component peak, we presented 1 kHz sinusoidal tones of increasing duration under two experimental conditions: constant stimulus intensity, and using a constant stimulus energy requirement, such that stimulus intensity is reduced with increasing duration. Specifically, if the stimulus amplitude is A, we generated a family of stimuli subject to the requirement that $A^2t = C$, where the constant, C, is determined by the SPL required at the shortest duration stimulus. In Experiment 1, we measure M100 amplitude as a function of stimulus duration while holding stimulus intensity constant. In Experiment 2, we measure M100 amplitude as a function of stimulus duration while holding energy constant and commensurately decreasing stimulus intensity. Thus we investigate the nature of the temporal integration processes that underlie the formation of the M100 component.

If the overall physical energy in a sound signal is accumulated with a relatively straightforward combination of stimulus intensity and duration attributes, then we may expect to find M100 amplitudes in response to energy-matched sounds to be roughly similar in magnitude. If, on the other hand, stimulus attributes such as duration and intensity contribute differentially to the accumulation processing leading to formation of the M100 component, then we may expect to find modulation in auditory responses. Specifically, if temporal integration processes are largely dominated by the peak intensity in a sound, then we may find larger M100 amplitudes in response to the shorter, more intense sounds and little variation as a function of stimulus type in Experiment 1 (constant intensity). Alternatively, if integration accumulation is largely driven by stimulus on-time or duration, then we may expect to find larger M100 amplitudes in response to longer duration stimuli and that this effect might persist in Experiment 2, even though, in this condition, the longer duration stimuli have reduced intensity.

MATERIALS AND METHODS

In each of the two reported experiments, six healthy adults with normal hearing volunteered to participate. Stimulus presentation and magnetoencephalographic recording were performed with the approval of the institutional committee on human research. Informed written consent was obtained from each subject.

Stimuli were presented using a Mac Quadra 800 computer with a Audiomedia II soundcard (DigiDesign, Palo Alto, CA) and Psyscope stimulus presentation software [12]. Stimuli were presented monaurally using Etymotic ER-3A earphones and air tubes designed for use with the MEG system (Etymotic, Oak Brook, IL). The frequency response of the system is flat (within ± 3 dB) up to 4 kHz. MEG recordings were made from the hemisphere contralateral to the ear of presentation. This procedure was repeated for each hemisphere. Presentation was blocked by stimulus condition. Each stimulus was presented 200 times per block in a passive listening paradigm. Blocks were presented in a pseudorandom order for each of the five stimulus conditions, for each hemisphere, for a total of 10 blocks for each experiment.

Neuromagnetic fields were recorded for each subject using a 37-channel biomagnetometer (MAGNES, BTi, San Diego, CA) in a magnetically shielded room. The sensor-array was placed over the temporal lobe, contralateral to the ear of stimulus presentation. Evoked response to a reference (400 ms duration) 1 kHz pure tone was evaluated to determine if the sensor array was positioned to effectively record the auditory evoked M100 field. Epochs of 600 ms duration (100 ms pre-stimulus onset and 500 ms post-stimulus onset) were acquired around each stimulus at a sampling rate of 2083 Hz with a bandwidth of 800 Hz and a 1.0 Hz high-pass filter.

The recorded data were selectively averaged by stimulus condition for each hemisphere. Averaged waveforms were band-pass filtered using a low cut-off frequency of 1 Hz and a high cut-off frequency of 40 Hz. The root mean square (RMS) of the field strength across all 37 channels was calculated for each sample point. The M100 peak was determined as the peak RMS value across 37 channels in the interval 80–150 ms, subject to a single equivalent current dipole model/data correlation $r > 0.97$. The M100 latency and amplitude peak served as dependent measures.

In Experiment 1, stimuli were 1kHz sinusoidal tones that varied in duration in five steps (10 ms, 20 ms, 40 ms, 80 ms and 250 ms) and were matched for intensity (Fig. 1a). In Experiment 2, stimuli were 1 kHz sinusoidal tones that varied similarly in duration (t) in five steps but were matched for overall physical energy according to the formula $A^2t = C$, where C is a constant. Thus, as stimulus duration increased, intensity decreased. Stimuli were synthesized using Labview software and consisted of five tones with the following duration and intensity levels: 10 ms, 70 dB SPL; 20 ms, 67 dB SPL; 40 ms, 64 dB SPL; 80 ms, 61 dB SPL; and 250 ms, 58 dB SPL (Fig. 1b).

Detection thresholds were obtained for each subject for each ear in response to the monaurally presented 10 ms stimulus and all five stimuli were presented at a gain 40 dB above that required for detection of this stimulus. Mean detection thresholds were similar across subjects, with an average difference of 2.75 dB (s.d. 1.89).

RESULTS

All stimuli reliably elicited an M100 evoked field response in each hemisphere, with an underlying modeled source in auditory cortex. In Experiment 1, a 5 (stimulus duration) × 2 (hemisphere) ANOVA with M100 component peak amplitude as the dependent measure produced a main effect of stimulus duration ($F(1,4) = 5.57$, $p < 0.009$). M100 amplitude was modulated as a function of stimulus profile, with increased amplitudes of evoked responses as stimulus duration increased (see Fig. 2). No significant difference in M100 component peak latency was observed between stimuli.

In Experiment 2, a 5 (stimulus profile) × 2 (hemisphere) ANOVA with M100 component peak amplitude as the

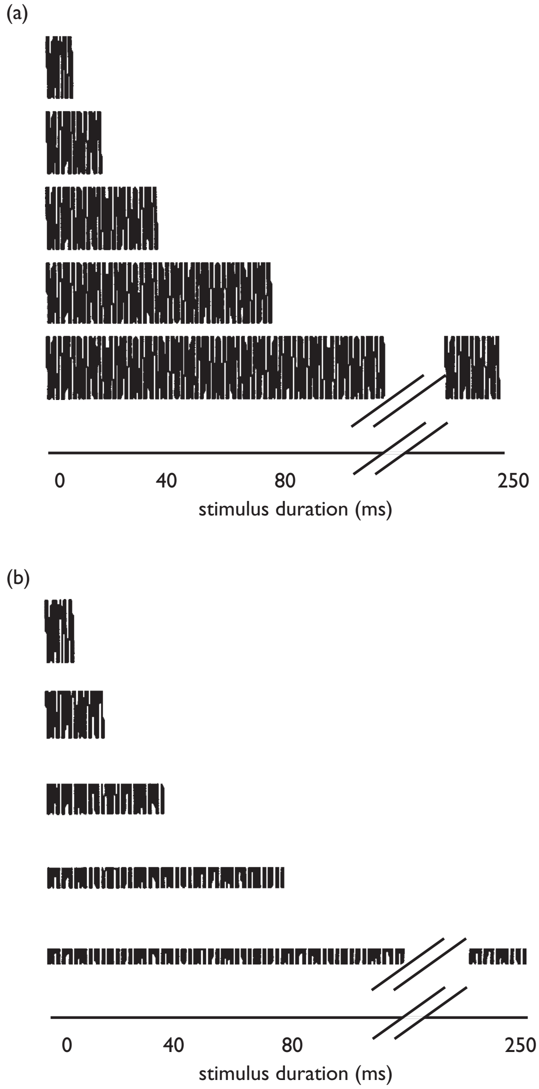

Fig. 1. (**a**) Sinusoidal 1kHz tone stimuli presented in Experiment 1. All tones were generated at constant amplitude, equivalent to 70 dB SPL. Stimulus duration varied in five steps: 10 ms, 20 ms, 40 ms, 80 ms and 250 ms. (**b**) Sinusoidal 1 kHz tone stimuli presented in Experiment 2. Stimulus duration and intensity varied as follows: 10 ms duration, generated at 70 dB SPL; 20 ms duration, generated at 67 dB SPL; 40 ms duration, generated at 64 dB SPL; 80 ms duration, generated at 61 dB SPL; and 250 ms duration, generated at 58 dB SPL.

dependent measure produced a main effect of stimulus duration ($F(1,4) = 10.83$, $p < 0.001$), similar to that observed in Experiment 1. M100 amplitude was modulated as a function of stimulus profile in both hemispheres, with increased amplitudes of evoked responses as stimulus duration increased, in spite of reduced stimulus intensity. M100 amplitude increases were again seen up to a saturation point of ~40 ms. This effect was characterized by a nearly linear rise in the amplitude of responses to the 10–40 ms stimuli, at which point the effect reached saturation and the response curve flattened (Fig. 2).

Again, no significant difference in M100 component peak latency was observed between stimuli in either the left ($F(1,4) = 1.30$, $p = 0.865$) or the right ($F(1,4) = 10.83$, $p = 0.311$) hemisphere. This result is generally consistent with previous findings, where M100 latency has been shown to reflect a frequency dependence that is largely independent of stimulus intensity level within the range tested here (58–70 dB SPL) [13].

DISCUSSION

Our findings in Experiment 1 indicate that auditory M100 amplitude is increasing with increasing stimulus duration, reaching a plateau at ~40 ms, replicating previous results [3,5], and provide evidence that there is a summation or accumulation of stimulus information, within such a finite temporal window of integration.

In Experiment 2, we held the physical energy in the stimuli constant and varied duration and intensity in order to investigate the relative contributions of these stimulus attributes on the accumulation processes underlying the formation of the M100 component. We report a stimulus duration dependence in the processes leading to the M100 peak, with M100 amplitude modulated as a function of stimulus duration in a similar fashion to the constant stimulus intensity condition (Experiment 1), with little or no further influence of stimulus intensity, at least within the range tested here (58–70 dB SPL). Our findings again indicate that this modulation reaches a point of saturation at a stimulus duration of ~40 ms. Specifically of note, the results of Experiment 2 indicate that the amplitude of the M100 is not strongly related to the integration of stimulus energy (since the stimuli were in fact matched for overall energy), but rather varied with stimulus duration itself (within the ~40 ms window).

It is important to emphasize that, in Experiment 2 of our study, M100 amplitude increased with stimulus duration in spite of the fact that the stimulus intensity level decreased rather sharply. For example, the stimulus of 40 ms duration was a full power level (6 dB) quieter (at 64 dB SPL) than the stimulus of 10 ms duration (70 dB SPL), yet response amplitude for the 40 ms stimulus was roughly 50% higher than that to the 10 ms stimulus. This general effect held for each subject, in both left and right hemispheres. Although prior MEG data, from our laboratory and others, have provided evidence for M100 amplitude modulation as a function of stimulus intensity [6–9], the present data indicate that, while intensity may be contributing in some manner to the accumulation processing, it is the stimulus duration that dominates the M100 amplitude modulation effect especially during this critical early phase. These data support the conclusion that stimulus duration is encoded in accumulation processes that underlie the auditory M100 and provides the primary modulating force in M100 amplitude within a range 0–40 ms.

CONCLUSION

The present data, based on observations of the amplitude variation of the M100 component of the auditory evoked field, provide evidence for an ~40 ms temporal window of integration during which stimulus attributes are accumulated in processes leading up to the formation of the M100 peak. This confirms previous studies suggesting similar temporal windows (25–32 ms). Interestingly, within the

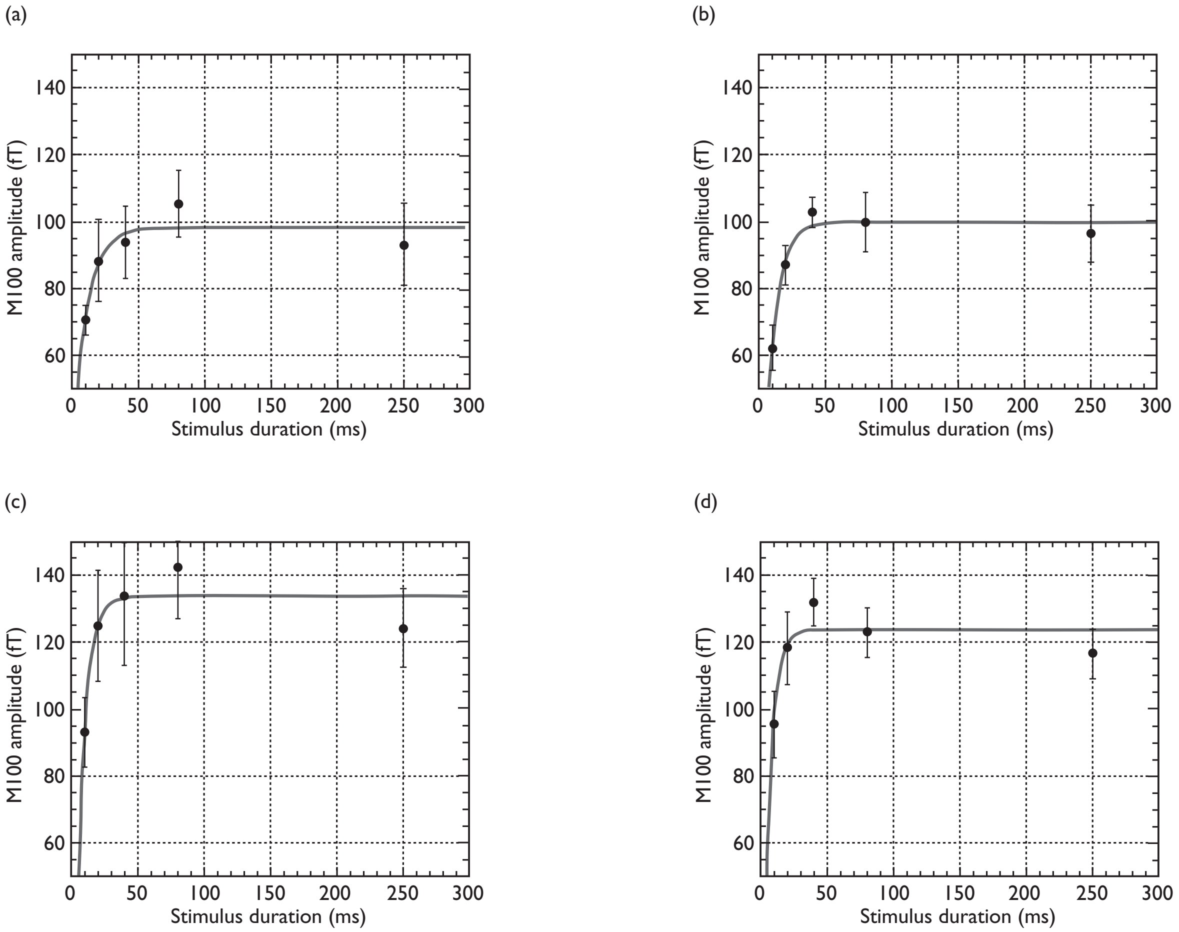

Fig. 2. Mean M100 amplitude (error bars reflect s.d. across subjects) for each of the five tone stimuli: (**a**) left hemisphere, Experiment 1 and (**b**) left hemisphere, Experiment 2. The horizontal axis plots stimulus duration (in ms). Curves reflect fits to an exponential recovery function, with time constants of 8.5–11 ms. Mean M100 amplitude (error bars reflect s.d. across subjects) for each of the five tone stimuli: (**c**) right hemisphere, Experiment 1 and (**d**) right hemisphere, Experiment 2. The horizontal axis plots stimulus duration (in ms). Curves reflect fits to an exponential recovery function, with time constants of 5.6–6.5 ms. Both Experiment 1 and Experiment 2 give rise to similar M100 amplitude response profiles. Time constants merely serve as descriptive measures of the response amplitude/stimulus intensity dependence and are not significantly different between experimental conditions, or hemispheres ($p > 0.05$).

considerably suprathreshold intensity ranges spanned by our stimuli, it is not the integration of stimulus energy during this temporal window which determines M100 amplitude, but rather stimulus duration itself.

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